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T. Becker, L. Kutzbach, I. Forbrich, Jodi Schneider, D. Jager, et al.. Do we miss the hot spots? ? The use of very high resolution aerial photographs to quantify carbon fluxes in peatlands. Biogeosciences Discussions, 2008, 5 (2), pp.1097-1117. hal-00297982

HAL Id: hal-00297982

<https://hal.science/hal-00297982>

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Do we miss the hot spots? – The use of very high resolution aerial photographs to quantify carbon fluxes in peatlands

T. Becker¹, L. Kutzbach¹, I. Forbrich¹, J. Schneider¹, D. Jäger¹, B. Thees², and M. Wilmking¹

¹Institute of Botany and Landscape Ecology, University of Greifswald, Grimmer Straße 88, 17489 Greifswald, Germany

²Federal Environmental Agency, Berlin, Germany

Received: 25 January 2008 – Accepted: 5 February 2008 – Published: 6 March 2008

Correspondence to: T. Becker (tbecker@uni-greifswald.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Accurate determination of carbon balances in heterogeneous ecosystems often requires the extrapolation of point based measurements. The ground resolution (pixel size) of the extrapolation base, e.g. a land-cover map, might thus influence the calculated carbon balance, in particular if biogeochemical hot spots are small in size. In this paper, we test the effects of varying ground resolution on the calculated carbon balance of a boreal peatland consisting of hummocks (dry), lawns (intermediate) and flarks (wet surfaces). The generalizations in lower resolution imagery led to biased area estimates for individual micro-site types. While areas of lawns and hummocks were stable below a threshold resolution of ~60 cm, the maximum of the flark area was located at resolutions below 25 cm and was then decreasing with coarsening resolution. Using a resolution of 100 cm instead of 6 cm led to an overestimation of total CO₂ uptake of the studied peatland area (approximately 14 600 m²) of ~6% and an underestimation of total CH₄ emission of ~11%. To accurately determine the surface area of scattered and small-sized micro-site types in heterogeneous ecosystems (e.g. flarks in peatlands), a minimum ground resolution appears necessary. In our case this leads to a recommended resolution of 25 cm, which can be derived by conventional airborne imagery. The usage of high resolution imagery from commercial satellites, e.g. Quickbird, however, is likely to underestimate the surface area of biogeochemical hot spots. It is important to note that the observed resolution effect on the carbon balance estimates can be much stronger for other ecosystems than for the investigated peatland where the relative hot spot area of the flarks is very small and their hot spot characteristics with respect to CH₄ and CO₂ fluxes is rather modest.

1 Introduction

Closed chambers have been frequently used to derive gas exchange balances between ecosystems and the atmosphere. Usually, representative plots within the ecosys-

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tem are selected, which cover the spatial heterogeneity of the study site. There, fluxes are measured, and the modeled seasonal gas exchange fluxes from these plots are extrapolated to larger areas or the whole ecosystem. Extrapolation is usually done based on the spatial representation of each measured micro-site within the ecosystem: a modeled flux of a particular representative micro-site is usually multiplied by the area that particular micro-site type occupies (Schimel and Potter, 1995).

The exact spatial distribution of micro-sites is in particular important, if micro-site size is small and the ecosystem surface strongly heterogeneous, e.g. in many peatland ecosystems. Spatial information on micro-site distribution can be obtained by rough estimation, vegetation mapping in a smaller area e.g. Riutta et al. (2007), along transects e.g. Alm et al. (1997) and Laine et al. (2006), or with a land-cover map of the complete area under study e.g. Bubier et al. (2005). While this last approach promises the most reliable spatial estimates and thus the most reliable flux extrapolation, it depends entirely on the relationship between the ground resolution of the imagery and the size of the micro-sites. Here, we show that ecosystem trace gas flux estimates, especially for methane, depend significantly on the resolution of the underlying land-cover map. We further develop recommendations for a reasonable ratio between size of micro-sites and resolution of the underlying landcover map.

2 Study site

The peatland “Salmisuo” is located at 62°47′N, 30°56′E, in Eastern Finland (Fig. 1), and is generally classified as an oligotrophic low-sedge pine fen (Saarnio et al., 1997). Climatic conditions represent the boreal forest climate (Strahler and Strahler, 2005) with a mean annual air temperature of +2.1°C and a mean annual precipitation of 667 mm (years: 1971–2000 in Finnish Meteorological Institute, 2002). The surface of the peatland consists of three main vegetation communities, which follow the micro-topography. Hummocks are elevated and drier areas, (*Pinus sylvestris*, *Andromeda polifolia*, *Sphagnum fuscum*), lawns are intermediate areas with respect to moisture

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conditions (*Eriophorum vaginatum*, *Sphagnum balticum*, *Sphagnum papillosum*), and flarks are wet areas (*Scheuchzeria palustris*, *Sphagnum balticum*).

3 Methods

The calculated carbon balance for this study is based on 1) plot-scale quantification of CO₂ and CH₄ exchange fluxes using closed chambers over 50 days, 2) a hydrological part to estimate the lateral carbon losses by dissolved organic carbon (DOC) and 3) a remote sensing part to map the spatial distribution of micro-sites.

3.1 Gas flux measurements

For this study, we analyzed CO₂ and CH₄ emission for the time period 26 July 2005–13 September 2005 (50 days): Fluxes of CO₂ and CH₄ were measured with the closed chamber technique (Alm et al., 2007).

Sample plots have been chosen by the three dominant types of micro-sites (flarks, lawns and hummocks). For every micro-site type four replicate sample plots have been used to achieve a representative mean value of the appropriate vegetation type.

CO₂ and CH₄ fluxes were measured once a week. The CO₂ measurements were performed over 24 h. For determination of net ecosystem CO₂ exchange, we employed a vented transparent chamber (60 cm×60 cm×32 cm) with an automatic cooling system which kept the headspace air temperature within approximately 1°C of the ambient temperature. The dark respiration and CH₄ flux measurements were conducted using vented aluminum chambers. The CO₂ concentrations were measured using a CO₂/H₂O infrared gas analyzer (LI-840, Licor, USA). CO₂ readings were taken at 1 s intervals over 180 s. During the CH₄ flux measurements, four headspace samples were taken every 4 min from the chamber in a 16 min time period. CH₄ concentration in the syringes were analyzed one day later with a gas chromatograph (Shimadzu 14-A) equipped with a flame ionisation detector. The gas fluxes were calculated from

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the concentration increase in the chamber headspace over time applying nonlinear regression for CO₂ (Kutzbach et al., 2007) and linear regression for CH₄. The seasonal time series of CO₂ and CH₄ exchange fluxes over the investigation period were modeled on a temporal resolution of 0.5 h for CO₂ and 1.0 h for CH₄ using multilinear regression models with photosynthetically active radiation, air temperature, peat temperature in 5 cm, air pressure, wind speed and water table as predictors of CO₂ fluxes and groundwater table, peat temperature in steps of 5 cm, 10 cm, 20 cm and 50 cm and wind speed as predictors for CH₄ fluxes. Then, the modeled time series of CO₂ and CH₄ fluxes were integrated to derive the total amount of CO₂ and CH₄ exchanged over the investigation period. The flux value for each micro-site type was then calculated as the mean of the four replicates.

3.2 Hydrology

Dissolved organic carbon (DOC) export was calculated by multiplying daily surface runoff with average daily DOC mass per volume concentrations ([DOC]); measurements were undertaken at a ditch collecting the peatland outflow. [DOC] was determined by daily water sampling and subsequent analysis of UV absorbance at 254 nm in a double beam UV/VIS spectrophotometer. For calibration of the UVVIS spectrophotometer, a selection of samples was analyzed with a Shimadzu 5000-A TOC analyzer for their [DOC] to establish a linear correlation between UV absorption and [DOC]. Discharge was measured by a sharp-crested v-notch weir. Discharge values were logged every 15 min and subsequently integrated to daily runoff values. The resulting daily DOC flux rates in the stream were converted to export values per unit area (in g C×m⁻²) through integration over time and then divided by the catchment area size (365 000 m²).

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3.3 Remote sensing

The remote sensing task was covered by very high resolution imagery taken from a helium filled dirigible. The dirigible with a volume of 2 m^3 was capable to lift 1 kg of payload and was with his tail fins well equipped to be more stable in the air than a balloon. At the bottom of the dirigible, a camera rig was attached that held the camera in an almost nadir position.

To obtain the imagery, we utilized a 7 megapixel point and shoot camera (Canon Powershot G6) combined with a 2 gigabyte storage medium. This setting provided us with the ability to obtain 100 raw data images (*.crw) per flight session with a resolution of 3072×2304 pixels and a shooting frequency of one image per minute. The restriction of 100 images was given by the software of the camera. The ground resolution of these imagery depends very much on the flying height of the platform (e.g. $\sim 5\text{ cm}$ at a flying height of 130 m above the ground).

For further processing the imagery was georectified using a grid of ground control points (GCPs). The grid had a cellwidth of about 50 m, and the position of every GCP was measured with a differential global positioning system. The average horizontal accuracy of these measurements was 35 cm.

In order to get a reasonable amount of GCPs for georectification and at the same time a very high ground resolution, a flying height of $\sim 150\text{ m}$ above the ground was chosen, offering a ground resolution of about 6 cm and a minimum of 6 GCPs in every image.

To simulate different flying heights of the dirigible, we coarsened the ground resolution from 6 cm to 10 cm and further in steps of 5 cm up to a resolution of 100 cm. By coarsening the resolution up to 100 cm we cover the range from very high resolution airborne imagery to very high resolution commercial satellite imagery (e.g. QuickBird 2 – 61 cm – and IKONOS 2 – 100 cm). Coarsening the resolution was done during the process of georectification in ER Mapper Professional 7.1 of ER Mapper, using the nearest neighbor algorithm to resample the imagery to the desired resolution (Earth

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Resource Mapping, 2006).

The georectified imagery was classified in the next step, defining regions to represent the micro-site types and using a supervised classification with the maximum likelihood algorithm in ER Mapper 7.1. The resulting land cover map (Fig. 2) was vectorized, using the Raster-To-Polygon function in ArcGIS of ESRI to proceed to the statistical analysis (ESRI, 2004).

Furthermore we calculated total area and average size of each micro-site type for each resolution (Table 1, Fig. 3).

To locate discontinuities in the data we conducted a moving split window analysis (Johnston et al., 1992). Using the moving split window a changing of the observed attribute is indicated by maximum values in the graphs. A four-sample window width was applied to find possible thresholds while coarsening the ground resolution.

4 Results

Highest obtained ground resolution was 6 cm and subsequent coarsening resulted in 20 area estimates (Fig. 3) for each micro-site type. Flark area was stable ($\sim 200\text{--}250\text{ m}^2$) below a threshold of $\sim 25\text{ cm}$ and then decreased with coarsening resolution (loss of 54 % between 6 cm and 100 cm) with the exception of the resolution between 55 cm and 80 cm, were values for flarks varied by up to 370 %. Area of lawns and hummocks ($\sim 7000\text{--}7200\text{ m}^2$) was stable until a threshold of $\sim 60\text{ cm}$. Coarser resolutions resulted in a linear increase of hummocks and a concurrent decrease in lawns (21 % change between 6 cm and 100 cm). The oscillation of the values in Fig. 3 is very likely the effect of a changing pixel pattern when resampling the imagery. Furthermore the selection of the training area for the algorithm and the variety of pixel values within these area adds fluctuations to the graphs. The big fluctuation in the class of flarks between a resolution of 55 cm and 80 cm is showing the unreliability of the data at these resolution. In comparison to these uncertainties Fig. 4 is showing a threshold for the class of flarks at a resolution of 60 cm. Due to the small contribution of flarks to the

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total area, estimates of lawns and hummocks behave nearly as mirror images of each other (Fig. 3). This effect is probably also related to the resampling and classification method. The amount of single objects in the classes of lawns and hummocks and their close spatial relationship is causing a give-and-take between these two classes at their common border. Hence the spatial representation of the two major classes depend on each other and a changing of much smaller classes has no reasonable effect.

Seasonal gas fluxes differed between micro-site types (Tab. 2) with flarks emitting the most CH₄ per area and hummocks taking up most of the CO₂ per area. Seasonal DOC export was calculated as $0.09 \pm 0.02 \text{ g C/m}^2$, representing only 0.44 % of the seasonal carbon balance. Taken together, the generalizations in lower resolution imagery lead to biased area estimates for the individual micro-site types (Fig. 3), and thus at a resolution of 100 cm to an overestimation of total CO₂ uptake of ~5.5 % (Fig. 5a) and an underestimation of total CH₄ emission of ~11 % (Fig. 5b).

The accuracy of gas flux estimations in this approach is highly related to the ground resolution of the imagery used for the classification. Due to stronger generalization at a smaller scale the loss of small objects is increasing by coarsening the pixel size.

To identify possible thresholds for the detection of large changes in the calculated area during the coarsening process and thus reasonable object sizes at the particular resolution (Fig. 4), we used the moving split window analysis (MSWA) e.g. Johnston et al. (1992). For every micro-site the lowest possible detection threshold, indicated by the peak, is located at a ground resolution of 25 cm. The next possible threshold for every micro-site is at a ground resolution of 60 cm.

Based on the results of the MSWA (Fig. 4) we calculated the mean object size for every micro-site type at ground resolutions of 25 cm and 60 cm (Table 3) to propose ratios for each micro-site type for the identification of objects in similar heterogeneous environments like the observed peatland (Table 4). We have choosen the mean object size to minimize influence of a dominating number of small objects at all resolutions.

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5 Discussion

The underestimation of methane fluxes at lower resolution, caused by the underestimated area of flarks and lawns, leads to a conservative approximation of the methane fluxes in the particular area. Using a ground resolution of 100 cm the total carbon budget is underestimated by $\sim 1.18 \text{ g/m}^2$ in the sample area, compared to the highest resolution of 6 cm. The total amount of effective greenhouse gases would be underestimated by $\sim 9.3\%$ between a ground resolution of 6 cm and 100 cm. Using land-cover maps with even lower resolutions (Takeuchi et al., 2003), would very likely increase this effect.

As shown in Fig. 3 the total area of individual micro-site types, depending entirely on the size and number of the associated polygons, is altered at a changing resolution. On the one hand this is caused by the generalization of details from high to lower resolution data (Jensen, 2000). On the other hand it is more difficult to identify smaller objects at lower resolutions, leading to errors during the classification process (Markham and Townshend, 1981). It is also possible, that the classification result is influenced by the data distribution, considering that the maximum likelihood algorithm assumes a normal distribution of the band data (Leica Geosystems GIS and Mapping, 2003).

The result of the MSWA indicates possible thresholds for the resolution of the imagery (Fig. 4). To achieve reasonable classification results in a peatland like Salmisuo a ground resolution of 25 cm is recommended to analyze small micro-sites (e.g. flarks). To analyze micro-sites as lawns and hummocks a ground resolution of 60 cm seems to be adequate. Both thresholds show that very high satellite imagery still tends to misjudge the distribution of the micro-sites (plant communities) in small patterned peatlands.

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6 Conclusions

We show that based on differing ground resolution of the land-cover map, substantially different areas for individual micro-site types are calculated. This influences the calculation of the carbon balance, since gas fluxes between the ecosystem and the atmosphere are measured at representative spots of each micro-site type and then multiplied by the micro-site area. In particular small micro-sites, which are often biogeochemical hot-spots, (e.g. wet areas emitting CH₄), tend to be affected. In our field site, a ground resolution of 25 cm seems to be necessary for the detection of these biogeochemical hot-spots with respect to CH₄ emission. A resolution of 60 cm seems sufficient for a representative detection of larger micro-site types as well as with respect to CO₂ fluxes for all micro-sites types. To successfully detect small micro-site types (e.g. flarks), we thus recommend a ratio of 1:2 of mean object size to image ground resolution and for larger micro-site types (e.g. lawns and hummocks) a ratio of 1:4.

Acknowledgements. Funding for this study was provided by a Sofja Kovalevskaja Research Award to M. Wilmking. I. Forbrich was supported by a Fellowship from the German Federal Environmental Foundation (DBU). T. Becker was partly supported by the German Academic Exchange Service (DAAD). We thank the Umweltbundesamt for support for Barnim Thees and all colleagues of the “Carbon in Peatlands” Conference in Wageningen for helpful discussions. Furthermore we like to thank A. Roberts of the Simon Fraser University in Burnaby, Canada for the use of his remote sensing laboratory and S. Wolf of the ETH Zurich, Switzerland for the generative and enjoyable discussions.

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Table 1. Total area covered by different micro-types; results based on classifications of different resolutions.

resolution	flark	lawn	hummock
6 cm	254 m ²	7156 m ²	7182 m ²
15 cm	255 m ²	7087 m ²	7500 m ²
100 cm	165 m ²	5641 m ²	9142 m ²

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Table 2. Seasonal gas fluxes of CH₄ and CO₂ for every micro-site type, estimated from closed chamber measurements; the DOC value is an estimate for the complete catchment.

	flarks	lawns	hummocks
CH ₄ -C	4.3±1.8 g/m ²	1.9±0.8 g/m ²	0.6±0.8 g/m ²
CO ₂ -C	10.6±0.03 g/m ²	-17.7±0.05 g/m ²	-20.9±0.08 g/m ²
DOC export flux		0.09±0.02 g C/m ²	

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Table 3. Mean object size of the different micro-site types at indicated thresholds; see Fig. 4.

resolution	flarks	lawns	hummocks
25 cm	0.15 m ²	0.92 m ²	1.12 m ²
60 cm	0.70 m ²	4.80 m ²	4.37 m ²

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Table 4. Ratio of mean object size to ground resolution; no ratio given for flarks at 60 cm due to determined threshold at 25 cm and unreasonable results at lower resolutions.

resolution	flarks	lawns	hummocks
25 cm	1:2	1:4	1:5
60 cm	–	1:4	1:4

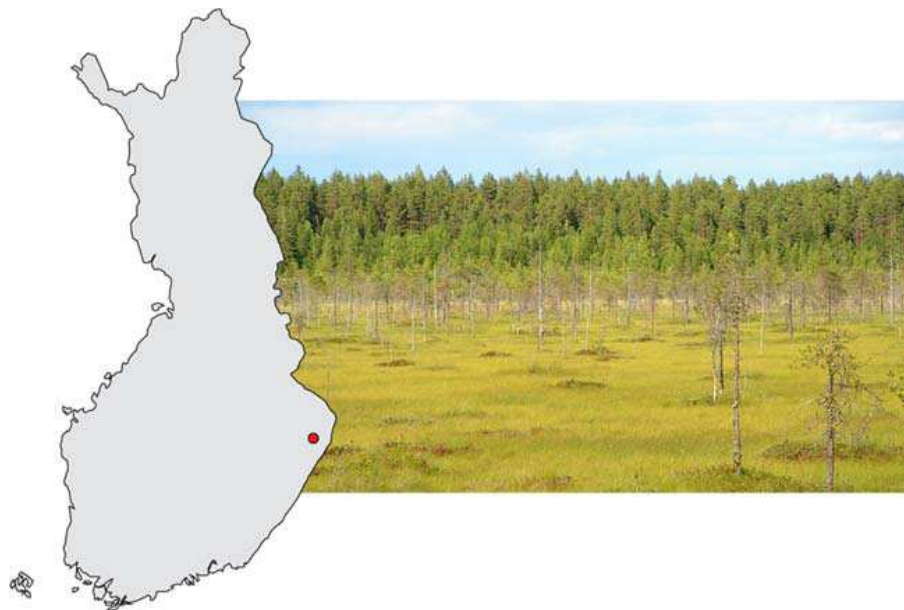


Fig. 1. Location of the study site in Finland, indicated by the red point.

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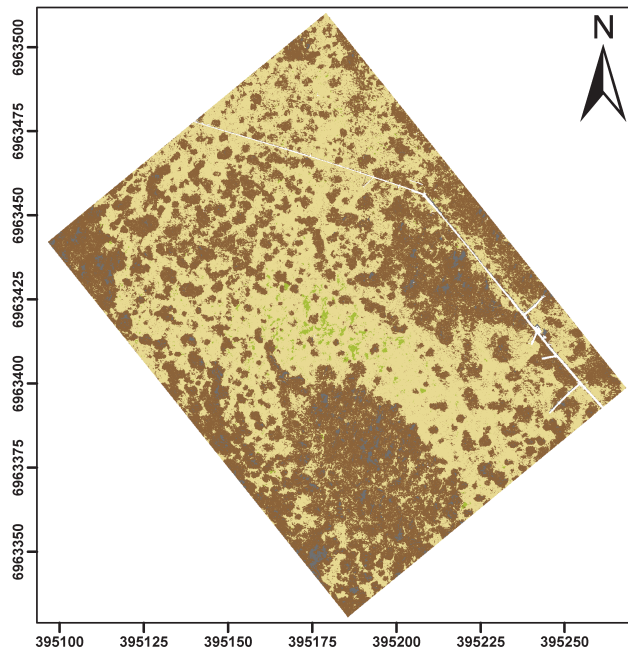


Fig. 2. Result of the maximum likelihood classification at a ground resolution of 6 cm; green=flarks, beige=lawns, brown=hummocks, dark gray=shadow, white=boardwalk and dead trees.

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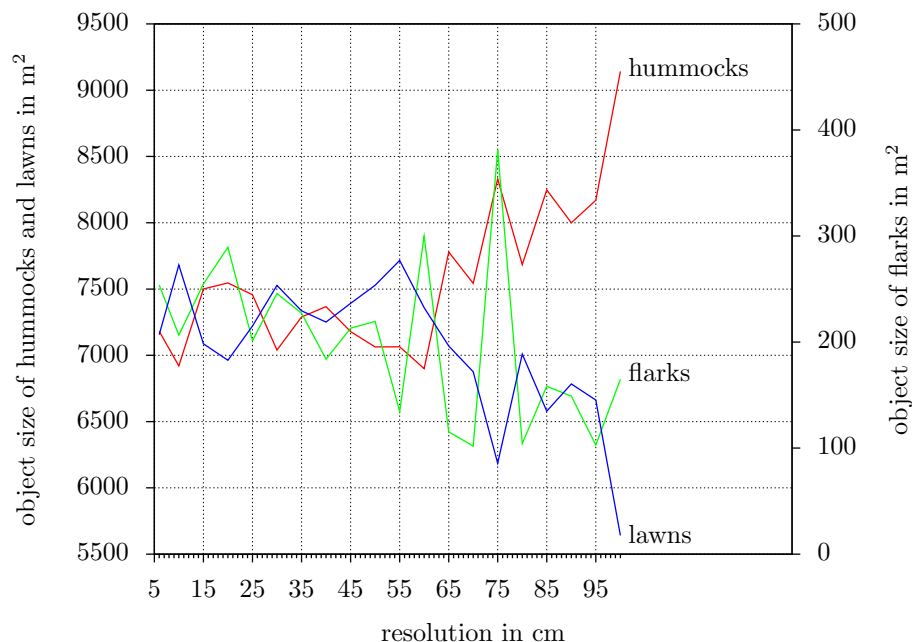


Fig. 3. Estimated total areas for flarks, lawns and hummocks at a stepwise coarsened ground resolution from 6 cm to 100 cm. The size of micro-sites is changing on a wide amplitude with changing resolution. Note different y-axes for hummocks/lawns and flarks, respectively.

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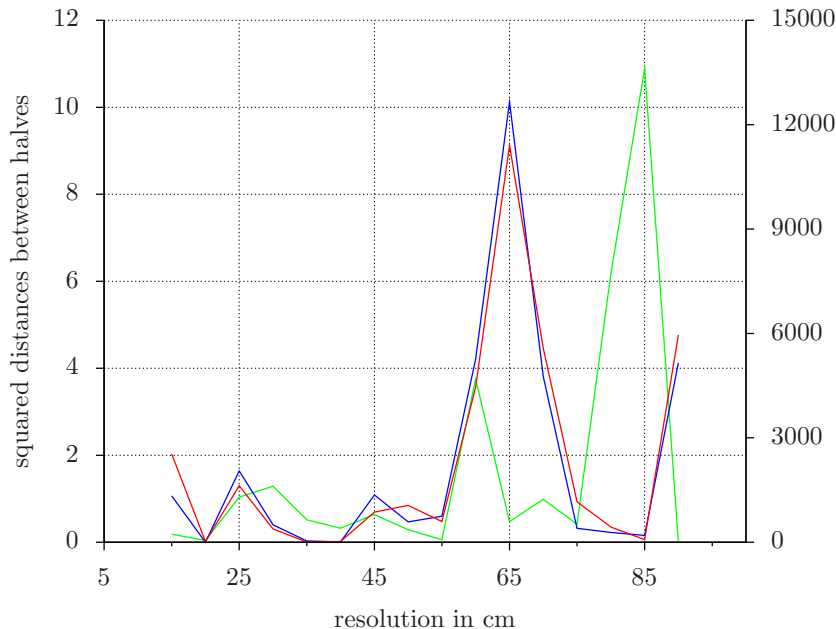


Fig. 4. Moving split window analysis of the total area covered by flarks, lawns and hummocks; the distances between the halves of the windows (y-axes) is plotted against the resolution (x-axes); The plot is showing the combined result of all three micro-sites, where the left y-axis belongs to lawn (blue) and hummocks (red) and the right y-axis to the flarks (green). Values on the left axis have to be multiplied by 100 000.

Do we miss the hot spots?

T. Becker et al.

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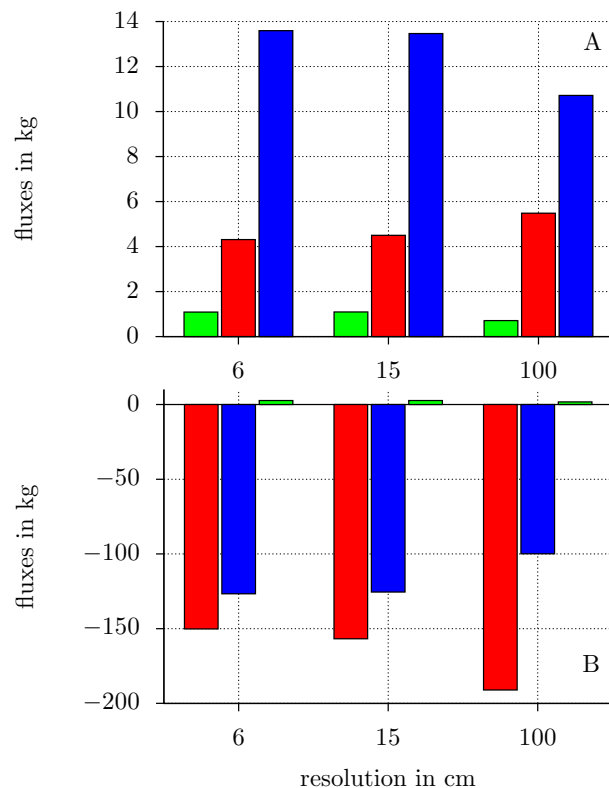


Fig. 5. Seasonal gas fluxes, calculated for the area of every micro-site type (green=flarks, blue=lawns, red=hummocks) at changing resolutions; **(A)**: seasonal fluxes of CH₄-C, grouped by resolution; at a resolution of 100 cm an underestimation of ~11 % of the total CH₄-C emission is shown; **(B)**: fluxes of CO₂-C, grouped by resolution; using a resolution of 100 cm instead of 6 cm lead to an overestimation of total CO₂-C uptake of ~5.5 %